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Jet-dominated states: an alternative to advection across black hole event horizons in 'quiescent' X-ray binaries

R. P. Fender[1], E. Gallo[1], P. G. Jonker[2]
[1] *Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands*
[2] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

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ABSTRACT

We demonstrate that at relatively low mass accretion rates, black hole candidate (BHC) X-ray binaries (XRBs) should enter 'jet-dominated' states, in which the majority of the liberated accretion power is in the form of a (radiatively inefficient) jet and not dissipated as X-rays in the accretion flow. This result follows from the empirically established non-linear relation between radio and X-ray power from low/hard state BHC XRBs, which we assume also to hold for neutron star (NS) XRBs. Conservative estimates of the jet power indicate that all BHC XRBs in 'quiescence' should be in this jet-dominated regime. In combination with an additional empirical result, namely that BHC XRBs are more 'radio loud' than NS XRBs, we find that in quiescence NS XRBs should be up to two orders of magnitude more luminous in X-rays than BHC XRBs, without requiring any significant advection of energy into a black hole. This ratio is as observed, and such observations should therefore no longer be considered as direct evidence for the existence of black hole event horizons. Furthermore, even if BHCs do contain black holes with event horizons, this work demonstrates that there is no requirement for the advection of significant amounts of accretion energy across the horizon.

Key words:
binaries: close – radio continuum: stars – ISM:jets and outflows – stars: neutron – black hole physics

1 INTRODUCTION

Proving the existence of black holes remains a key goal of observational high energy astrophysics. While dynamical evidence (e.g. Charles 1998) convincingly demonstrates the existence of compact accreting objects in binary systems which have masses in excess of the highest theoretical limit for a neutron star ($\sim 3M_{\odot}$), and are therefore strong black hole candidates (BHCs), we cannot rule out the possibility that some as-yet-unconsidered state of matter may provide an alternative explanation.

As an alternative approach, in recent years much attention has been focussed on finding evidence for black hole event horizons. One promising and actively pursued route has been a comparison of the X-ray luminosities of BHC and neutron star (NS) X-ray binaries (XRBs) in 'quiescence'. In such states, black hole accretion could be advection dominated and considerably fainter than neutron stars. This is indeed what has been found observationally, with 'quiescent' BHCs being typically two to three orders of magnitude (in Eddington units) less luminous than their NS XRB equivalents. This has been claimed to represent some of the strongest evidence to date for the existence of black hole event horizons (Narayan, Garcia & McClintock 1997; Menou et al. 1999; Garcia et al. 2001). However, alternatives to this interpretation have also been discussed (Campana & Stella 2000; Bildsten & Rutledge 2000; Abramowicz, Kluzniak & Lasota 2002). Abramowicz et al. (2002), in particular, stress that 'absence of evidence is not evidence of absence', and draw attention to alternatives to black holes. Even if BHCs *do* contain black hole with event horizons, it is important to establish how much, if any, of the potential accretion energy may be being advected across their horizons.

In a series of important and related observations, in recent years it has been established that jets are an integral and relatively ubiquitous component of the process of accretion in both black hole and neutron star X-ray binaries (e.g. Mirabel & Rodriguez 1999; Fender 2002). We are now beginning to understand just how powerful these jets may be. Corbel et al. (2003) discovered that, over four orders of

magnitude in X-ray luminosity, the relation between radio and X-ray luminosity for the BHC X-ray binary GX 339-4 has the form $L_{\rm radio} \propto L_{\rm X}^b$, where $b = 0.706 \pm 0.011$ for $L_{\rm X}$ in the 3–9 keV range (b increases slightly with the increasing energy of the X-ray band used for comparison). Gallo, Fender & Pooley (2003) demonstrated that the same relation holds over a comparable range in X-ray luminosity for the transient V404 Cyg (GS 2023+338), and furthermore that the data for all measured low/hard state sources is consistent with a such a Universal relation holding for all of them. This power law relation between radio and X-ray luminosity is a key observational discovery providing clues to the underlying physics of the disc–jet coupling.

Are there differences in jet power between the BHCs and NS XRBs ? Fender & Kuulkers (2001) found that BHC XRBs were, in general between 10–100 times more 'radio loud' (in the sense of the radio to soft X-ray ratio) than neutron star binaries. Migliari et al. (2003) compared the radio strength of the atoll-type neutron star binary 4U 1728-34 with the comparable state and X-ray luminosity of BHCs, and found a ratio of radio loudness $R_{\rm radio} = (L_{\rm radio}/L_{\rm X})_{\rm BH}/(L_{\rm radio}/L_{\rm X})_{\rm ns} \sim 30$. The origin of this difference in radio loudness is not clear (see Fender & Kuulkers 2001 for a discussion).

2 JET-DOMINATED STATES IN BLACK HOLE CANDIDATES

In the following all luminosities and accretion rates are in Eddington units, where the Eddington luminosity is $\sim 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}, where M is the mass of the accreting compact star. The Eddington accretion rate, defined as that accretion rate at which the Eddington luminosity is achieved, is, for an accretion efficiency of $\sim 10\%$ (ie. $\sim 0.1\dot{m}c^2$ is liberated during the accretion process) approximately $1.4 \times 10^{18}(M/M_\odot)$ g s^{-1}.

We assume that the total power output $L_{\rm total}$ from an X-ray binary in a 'low/hard' or analogous state is a combination of the radiative luminosity of the flow ($L_{\rm X}$, directly observed as X-rays) and jet power ($L_{\rm J}$ indirectly traced by e.g. radio flux density):

$$L_{\rm total} = L_{\rm X} + L_{\rm J} \quad (1)$$

Now we already know (Corbel et al. 2002; Gallo et al. 2003) the relation between radio ($L_{\rm radio}$) and X-ray luminosity:

$$L_{\rm radio} \propto L_{\rm X}^{0.7} \quad (2)$$

How does observed radio flux relate to jet power; i.e. what is the relation between $L_{\rm radio}$ and $L_{\rm J}$? In models of optically thick jets (e.g. Blandford & Königl 1979; Falcke & Biermann 1996; Markoff, Falcke & Fender 2001; Heinz & Sunyaev 2003), the following scaling applies:

$$L_{\rm radio} \propto L_{\rm J}^{1.4} \quad (3)$$

Combining equations (2) and (3):

$$L_{\rm J} \propto L_{\rm X}^{0.5} \quad (4)$$

therefore

$$L_{\rm total} = L_{\rm X} + A L_{\rm X}^{0.5} \quad (5)$$

which provides the relation between total power and X-ray luminosity. The normalisation A between can be estimated. Fender (2001) and Corbel & Fender (2002) conservatively estimate $L_{\rm J}/L_{\rm X} \geq 0.05$ for Cyg X-1 and GX 339-4 at an accretion luminosity of $L_{\rm X} \sim 10^{-2}$. Fender et al. (2001) estimated that, at an accretion luminosity of $L_{\rm X} \sim 10^{-3}$, the black hole transient XTE J1118+480 had $L_{\rm J}/L_{\rm X} \geq 0.2$ (see also Corbel & Fender 2002 for an estimate for GX 339-4). Conservatively adopting the equality for XTE J1118+480 corresponds to $A_{\rm BH} \sim 6 \times 10^{-3}$ in Eddington units. Equivalently the relation between total power and jet power is given by:

$$L_{\rm total} = A^{-2} L_{\rm J}^2 + L_{\rm J} \quad (6)$$

In the following we shall assume that $L_{\rm total}$ is proportional to the mass accretion rate $\dot{m}$ (i.e. all the available accretion power goes either into the X-rays or the jet). In Eddington units this corresponds to

$$L_{\rm tot} = \dot{m} \quad (7)$$

which is the condition of no advection of accretion energy across the event horizon.

We can then plot the variation of $L_{\rm X}$ and $L_{\rm J}$ as a function of mass accretion rate. These are plotted for black holes in the top panel of Fig 1.

We note that there are two regimes, 'X-ray dominated' at higher mass accretion rates, and 'jet dominated' at lower accretion rates. In the X-ray dominated regime, $L_{\rm X} \propto \dot{m}$ and $L_{\rm J} \propto \dot{m}^{0.5}$. However in the jet dominated regime $L_{\rm X} \propto \dot{m}^2$ and $L_{\rm J} \propto \dot{m}$. The transition between the two regimes occurs at $L_{\rm X} = A^2 \sim 4 \times 10^{-5}$ or, equivalently, $\dot{m} = 2A^2 \sim 7 \times 10^{-5}$. The shaded region in the top panel of Fig 1 indicates the observed range of X-ray luminosities of black hole X-ray binaries in 'quiescence' – if our model is correct then *all* of these systems are in the jet-dominated regime, with accretion rates $10^{-6} \lesssim \dot{m} \lesssim 10^{-5}$, and with jet powers one to two orders of magnitude greater than the observed X-ray luminosity.

3 JET-DOMINATED STATES IN NEUTRON STARS ?

A major uncertainty in knowing if the arguments outlined above apply to neutron stars is that the relation $L_{\rm radio} \propto L_{\rm X}^b$ has not yet been measured. Migliari et al. (2003) note that the relation seems steeper ($b > 1$) for the atoll-type X-ray binary 4U 1728-34, but this is over a small range in X-ray flux compared to that measured for black holes. At present we must consider that this relation remains unmeasured, due primarily to the relative faintness of atoll-type sources in the radio band compared to black holes (Fender & Hendry 2000), which results from the greater 'radio loudness' of black holes (Fender & Kuulkers 2001; Migliari et al. 2003). However, we will make the assumption in what follows that the same relation does indeed apply for atoll-type NS XRBs.

As already noted, the ratio of 'radio loudness' between BHC and NS XRBs is $R_{\rm radio} \sim 30$. Using equation (3), this translates into a difference in jet power of a factor 10, i.e. $A_{\rm NS} \sim 6 \times 10^{-4}$. The X-ray luminosity below which neutron star systems would be jet-dominated is therefore $L_{\rm X} \sim 3 \times$

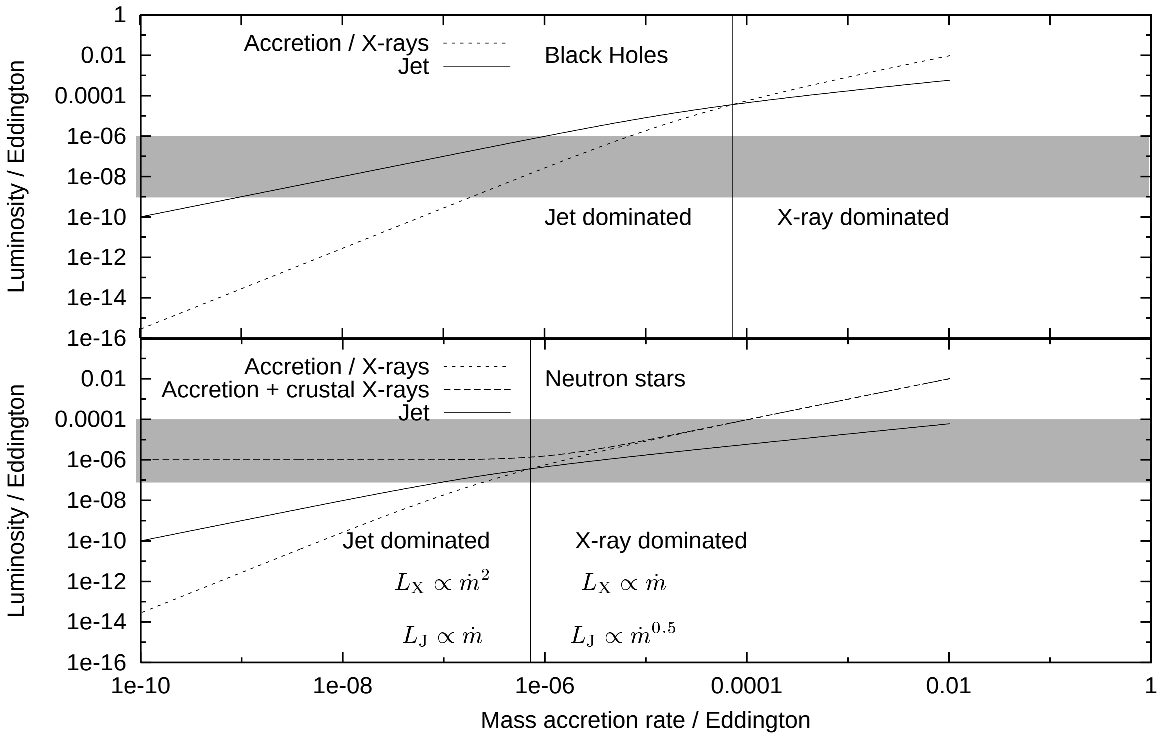

Figure 1. Variation of X-ray luminosity and jet power as a function of mass accretion rate, in our model, for neutron star and black hole X-ray binaries. Two regimes exist, 'X-ray dominated' and 'Jet dominated', with the transition from the former to the latter occurring at two orders of magnitude lower accretion rate in neutron stars than in black holes, due to their lower 'radio loudness'. In the 'X-ray' dominated regime, $L_{\rm X} \propto \dot{m}$, but in the 'Jet dominated' regime $L_{\rm X} \propto \dot{m}^2$. The transition between the two regimes occurs at an X-ray luminosity $L_{\rm X} = A^2$, where $A_{\rm BH} \sim 6 \times 10^{-3}$ and $A_{\rm NS} \sim 6 \times 10^{-4}$. The shaded areas indicate the range of X-ray luminosities observed in 'quiescence' from the two types of X-ray binary. If this model is correct, *all* of the quiescent black hole binaries are in the jet-dominated regime.

10^{-7}. This is comparable to the lowest X-ray luminosity measured from a neutron star in quiescence (Garcia et al. 2001) implying that, quite unlike black holes, we may have never observed a neutron star in a jet-dominated state. In the lower panel of Fig 1 we plot the variation of $L_{\rm X}$ and $L_{\rm J}$ as a function of mass accretion rate for neutron star binaries. As for the BHCs, the shaded region indicates the observed range of 'quiescent' X-ray luminosities.

In the absence of core/crustal emission (see below) which is decoupled from the accretion flow on all but the longest timescales, the observed X-ray luminosities of 'quiescent' NS XRBs correspond to a range in accretion rate of $10^{-6} \lesssim \dot{m} \lesssim 10^{-4}$, overlapping with the range in $\dot{m}$ for 'quiescent' black holes. Therefore, in at least this respect, in the model presented here the data are consistent with both NS and BHC XRBs in 'quiescence' accreting at the same rate.

3.1 Core / crustal emission?

Brown, Bildsten & Rutledge (1998) have argued that, once accretion has halted, neutron stars will have a luminosity in the range 5×10^{32} – 5×10^{33} erg s^{-1} from crustal emission. This model seems to be supported by observations of transient neutron star binaries in quiescence (e.g. Rutledge et al. 2001a; Rutledge et al. 2001b; Rutledge et al. 2002; see also Wijnands et al. 2001), although Garcia et al. (2001) argue that even at 'quiescent' levels the X-ray luminosity is dominated by accretion. Indeed, the quiescent emission of SAX J1808.4–3658 is uncomfortably low (5×10^{31}erg s^{-1}) and hard (power law index 1.5 with a blackbody contribution of less than 10 per cent) for the neutron star crustal emission model unless the neutron star is more massive than 1.7 M$_\odot$ (Campana et al. 2002).

If this crustal emission does exist then it adds a new term to the total observed X-ray emission:

$$L_{\rm X,observed} = L_{\rm X} + L_{\rm crustal} \quad (8)$$

In Fig 1 (lower panel) we also indicate the solutions with the addition of persistent 'crustal' emission to the observed X-ray flux from a neutron star, at a level of 10^{32} erg s^{-1}, approximately the lowest luminosity observed from a quiescent neutron star. This has a significant effect, since this crustal luminosity, at $\sim 10^{-6} L_{\rm Edd}$ is above that at which neutron stars would enter the jet-dominated regime. Whereas in the case of accretion-only luminosity, while we had not observed neutron stars in jet-dominated regimes they were still possible, if such crustal luminosities are ubiquitous then neutron stars will not enter the jet-dominated

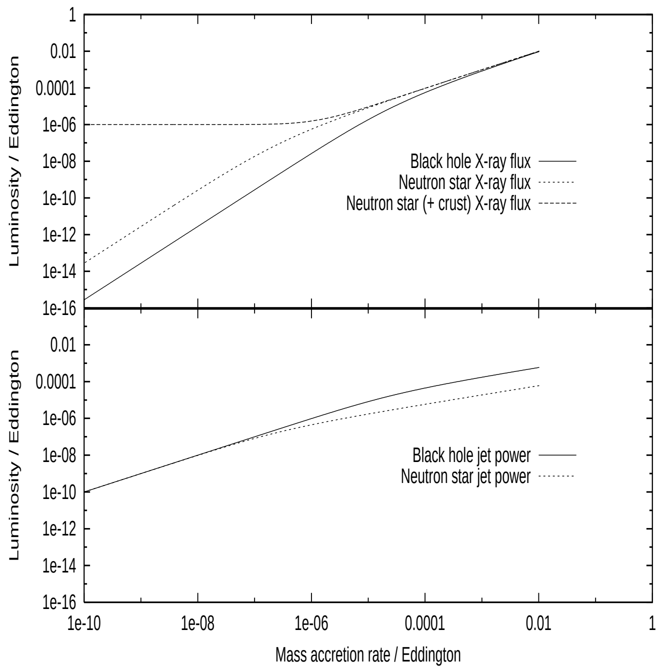

Figure 2. Variation of X-ray luminosity (upper panel) and jet power (lower panel) as a function of mass accretion rate for the model outlined in the text. Since black holes transit to the 'Jet dominated' regime at two orders of magnitude higher accretion rate than neutron stars (Fig 1), once both classes of system are in this regime (accretion rates corresponding to 'quiescence') then neutron stars will remain a factor of $Q_{\rm X} \sim 130$ more luminous in X-rays. This ratio, is consistent with observations of BHCs and NS XRBs in quiescence. Furthermore note that at very low accretion rates ($\dot{m} \leq 10^{-6.5}$) the jet power from BHCs and NS XRBs is the essentially the same, despite the NS XRBs being 100 times more luminous in X-rays, and 'quiescent' NS and BHC XRBs may be accreting at the same rate.

regime, unless their time-averaged mass accretion rates are very low ($\dot{m} \lesssim 10^{-12} M_{\odot}\ yr^{-1}$). However, note that at the lowest accretion rates neutron stars will make just as powerful jets as BHCs (see next section).

4 DISCUSSION

This work leads naturally to some interesting consequences if correct. We outline these below.

4.1 X-ray luminosity as a function of mass accretion rate

We have seen in the above that below a certain mass accretion rate BHC X-ray binaries probably enter a jet-dominated state. Because of their higher 'radio loudness', black holes make the transition to this jet-dominated state at a higher mass accretion rate than neutron stars (by a factor $(A_{\rm BH}/A_{\rm NS})^2$). Consequently, if there are no other effects, once both NS and BH are in the jet-dominated regime, the NS systems will be a factor $(A_{\rm BH}/A_{\rm NS})^2$ brighter in X-rays than the BH systems. Since $(A_{\rm BH}/A_{\rm NS}) \sim 10$ then we expect a ratio of ~ 100 between quiescent X-ray luminosities at the same accretion rate. In fact, while the expressions and plots given so far are specifically for the condition in equation (3) and the estimated values of $A_{\rm BH}$, $A_{\rm NS}$, there is a more general expression for the ratio of X-ray luminosities when both classes of object are in the jet-dominated regime:

$$Q_{\rm X} = (L_{\rm X})_{NS}/(L_{\rm X})_{\rm BH} = R_{\rm radio}^{1/b} \quad (9)$$

Since $R_{\rm radio} \sim 30$ and $\beta \sim 0.7$, we expect a ratio of X-ray luminosities in quiescence of ~ 130, when both BHCs and NS XRBs are in the jet-dominated regime, and at the same mass accretion rate. This is consistent with what is observed.

The X-ray luminosities as a function of $\dot{m}$ are illustrated in Fig 2 (top panel). As already noted, the quiescent NS XRBs may not be quite in the jet-dominated regime; however, the BHC XRBs are clearly in this regime, and the difference in X-ray luminosities at the same accretion rate is already one order of magnitude at $\dot{m} \sim 10^{-5}$, increasing to $Q_{\rm X}$ at $\dot{m} \sim 10^{-6}$ (Fig 2, top panel). We therefore find that the observed $L_{\rm radio} \propto L_{\rm X}^{0.7}$ scaling, combined with the order of magnitude greater radio loudness of BHC XRBs, naturally results in a signficant difference in the quiescent luminosities of NS and BHC XRBs, as observed.

More precisely, we expect there to be three regimes in which the ratio of X-ray luminosities, $R_{\rm X} = (L_{\rm X})_{\rm BH}/(L_{\rm X})_{\rm NS}$ has different values:

$$\begin{array}{llll} \text{(a)} & (L_{\rm X})_{\rm BH} \geq A_{\rm BH}^2 & (L_{\rm X})_{\rm NS} \geq A_{\rm NS}^2 & R_{\rm X} = 1 \\ \text{(b)} & (L_{\rm X})_{\rm BH} \leq A_{\rm BH}^2 & (L_{\rm X})_{\rm NS} \geq A_{\rm NS}^2 & 1 \leq R_{\rm X} \leq Q_{\rm X} \\ \text{(c)} & (L_{\rm X})_{\rm BH} \leq A_{\rm BH}^2 & (L_{\rm X})_{\rm NS} \leq A_{\rm NS}^2 & R_{\rm X} = Q_{\rm X} \end{array}$$

where (a) corresponds to both classes of objects being 'X-ray dominated', (b) corresponds to BHCs being jet-dominated and NS not, (c) corresponds to both classes being jet-dominated. From this study it appears that $Q \sim 130$, and that observed 'quiescence' corresponds to regimes (a) or (b), which consistent with the observations without requiring any accretion energy to be advected across an event horizon.

It is interesting to note that in the jet-dominated regime, the scaling of X-ray luminosity with mass accretion rate, $L_{\rm X} \propto \dot{m}^2$ is exactly the same as that predicted theoretically by ADAF models (e.g. Narayan et al. 1997; Mahadevan 1997).

4.2 Jets at the lowest accretion rates

It would be a mistake to assume that the persistent difference in X-ray luminosity will result in a difference in jet powers between NS and BHC systems at the lowest luminosities. In fact, below an accretion rate of $\dot{m} \sim 10^{-6.5}$ both NS and BHC systems are putting the same amount of power into the jet (Fig 2, lower panel), which dominates the power output of the system. The tiny fraction of the total power released as X-rays is insignificant whether its a BHC or a NS XRB one hundred times brighter.

It is also interesting to note that the ratio in radio loudness, $R_{\rm radio}$ is maintained throughout this scenario, but for somewhat different reasons in the two regimes. When 'X-ray dominated', BHCs are more 'radio loud' because they match

the NS XRBs in X-rays but put out more radio power. However, at the lowest accretion rates the radio power is the same but the X-ray luminosity of the BHCs is lower, maintaining the ratio.

4.3 X-ray jets: what if 'hard' X-ray binaries are already jet-dominated ?

It has been suggested that the hard X-ray spectra observed from low/hard state BHCs may be in some, maybe all, cases optically thin synchrotron emission directly from the jet (Markoff, Falcke & Fender 2001; Markoff et al. 2003). This is at odds with the more standard view of the hard X-ray spectrum as being dominated by thermal Comptonisation from electrons with a temperature of ~ 100 keV (e.g. Sunyaev & Titarchuk 1980; Poutanen 1998, Zdziarski et al. 2003). If it is the correct interpretation, how does it affect the analysis performed here ?

Since in those models the BHCs are already completely jet dominated at $\dot{m} = 0.01$, then $L_{\rm X} \propto \dot{m}^2$ (as $L_{\rm X} \propto L_{\rm J}^2$ [equation (4)] and $L_{\rm J} \propto \dot{m}$ this is always the case for jet-dominated emission). In fact it can be shown that the same ratio of 'quiescent' luminosities is achieved as in the previous analysis, as long as the NS XRBs are *not* already jet-dominated at $\dot{m} \sim 0.01$ (otherwise $L_{\rm X}$ in both classes of objects would track each other). However, the transition to the jet-dominated regime would occur at a higher $\dot{m}$ (by approximately two orders of magnitude), meaning the observed 'quiescent' mass accretion rates would be considerably higher than those indicated in Fig 1.

5 CONCLUSIONS

The results presented in this Letter are necessarily a subset of the possible consequences of the empirical relations and model upon which they are based. Of the more general results, to be expanded upon in a further work, only one is given, namely that once both BHC and NS XRB are in jet dominated states the ratio of X-ray luminosities depends only upon two quantities which have already been measured, i.e. b and $R_{\rm radio}$:

$$Q_{\rm X} = R_{\rm radio}^{1/b} \sim (30)^{1/0.7} \sim 130 \qquad (9)$$

We suggest that based upon existing observational data, 'quiescent' BHCs are in the 'jet-dominated' regime and that NS XRBs are, if not jet-dominated, close to the transition to this regime. Specifically, if a similar value of b holds for NS XRBs as for BHCs (and this is the key observational uncertainty) then quiescent NS XRBs are, in the most conservative case, putting $\gtrsim 10\%$ of their power into jets. Thus the observed ratio of X-ray luminosities should be close to $Q_{\rm X}$, consistent with what is observed. An additional core / crustal contribution to the X-ray emission from NS XRBs will only widen the discrepancy. Essentially, we find that the difference in quiescent X-ray luminosities between NS and BHC XRBs can be mostly, if not entirely, explained by a difference in the efficiency of jet production between the two types of sources (the origin of which remains unclear).

Therefore we find that the observed difference in quiescent luminosities of neutron star and black hole candidate XRBs *does not require the presence of black hole event horizons*. This should not be taken as a statement to the effect that we do not believe that black hole candidates contain black holes (see related discussion in Abramowicz et al. 2003). Certainly there are differences between the neutron star and black hole candidate XRBs, which may be naturally explained by the fact that black hole candidates do in fact contain black holes. However, since there is no requirement for significant energy to be advected into the black hole in order to explain the ratio of quiescent X-ray luminosities, these luminosities cannot in turn be taken as 'proof' of the existence of event horizons.

Furthermore, even if, as seems probable, the BHCs do contain black holes with event horizons, this work shows that there is no requirement for the advection of any significant quantity of accretion energy across the horizon. Rather, the relative radiative inefficiency of BHCs compared to NS XRBs at low $\dot{m}$ is due to the low radiative efficiency of the *jets* they are powering, not the accretion flow itself.

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